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4.	Title of the invention	INTERFEROMETER OPTICAL ELEMENT ALIGNMENT
5.	Name of your agent *(if you have one)* "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* Patents ADP number *(if you know it)*	Marks & Clerk Sussex House 83-85 Mosley Street Manchester M2 3LG 18004
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INTERFEROMETER OPTICAL ELEMENT ALIGNMENT

The present invention relates to a method and apparatus for aligning an optical element such as a mirror, and in particular a mirror of an optical interferometer.

Two-beam optical interferometers are widely used in optical measurement apparatus. Applications of such interferometers include the alignment and testing of optical systems and elements, such as compound lenses and communication systems using optical fibres. Interferometers make it possible to measure small differences in optical phase between an ideal beam (generally referred to as the reference beam) and a further beam which has been transmitted through or reflected by a lens, mirror or other optical component which is under test. The Twyman-Green interferometer is one example of this type of instrument although there are many others.

Two-beam interferometers are known in which an optical path difference is deliberately generated and varied in a controlled manner. Such interferometers, of which the Michelson interferometer is one example, are widely used for spectral analysis, particularly for the visible or near infrared regions of the electromagnetic spectrum. Michelson interferometers have many industrial applications, particularly in the chemical and pharmaceutical industries, and are used for process control and quality monitoring in a very wide range of industrial applications.

Optical testing and spectral analysis instruments call for high precision so as to maintain precisely known optical path differences between optical beams of the instrument. Alignment of optical components must be achieved before the interferometer is used, and maintained during use. This calls for a high degree of stability and precision with regard to both optical and mechanical characteristics.

In a typical Michelson interferometer, a broadband infrared source provides an infrared beam which is directed towards an infrared detector. The interferometer is used to perform spectral measurements for samples. The infrared beam is directed towards a beam splitter located between a fixed mirror and a moveable mirror, the two mirrors being arranged at 90° to each other. The beam is split into two components, one of which is reflected by the beam splitter towards the fixed mirror and back through the beam splitter to the detector, and the other of which passes through the beam splitter to the moveable mirror and is reflected back from the

moveable mirror by the beam splitter. The two component beams are recombined as they travel towards the detector from the beam splitter. The intensity sensed by the detector depends upon the optical path difference between the two component beams. By varying the relative distance (retardation) of one mirror from the beam splitter the optical path difference between the two beam paths can be varied. This in turn varies the intensity of the detected light in a way that reveals the spectral structure of the incident beam. This spectral structure can in turn be used to determine characteristics of the beam source and material that the beam has either passed through or been reflected from in the instrument. In addition, generally at least one monochromatic light source is arranged adjacent the main infrared beam but separate from it. The monochromatic source is used to determine the relative retardation of the mirrors and to assist in stabilising the mirrors during retardation.

Clearly the precise positioning of the mirrors relative to each other and the precise movement of the moveable mirror are fundamental to the accuracy of the instrument. Thus the mirrors must be initially aligned in a correct manner and their alignment must be maintained during use, and in particular during movement of the moveable mirror as the instrument is used. Generally initial alignment is achieved by a skilled technician visually inspecting a diffraction pattern incident upon the detector and making adjustments to the mirror angles accordingly. This alignment process must be repeated each time that the instrument is switched on and should be repeated at regular intervals to ensure that the instrument has not become misaligned for example as a result of exposure to a mechanical shock or vibration. Once initial alignment has been achieved, a dynamic control system is required to maintain the mirrors in alignment during mirror movement. Various proposals have been made for achieving the necessary dynamic alignment, for example that described in US Patent No. 5,657,122. That document describes a Michelson interferometer in which, in addition to the infrared beam used for measurement purposes, three parallel monochromatic beams are directed through the instrument towards respective ones of a triangular array of detectors provided for alignment purposes. The alignment detectors provide respective output signals which control three actuators arranged in a corresponding triangular array. The outputs of the three detectors drive the actuators to cause minute adjustment to the angular orientation of the nominally fixed mirror

thereby to compensate for wobble or systematic tilt of the nominally moveable mirror. This system does purport to maintain alignment during instrument use but does not purport to provide initial alignment which still requires the intervention of a skilled technician.

It is an object of the present invention to provide a method and apparatus for aligning an optical element such as a mirror of an optical interferometer.

According to the present invention, there is provided a method for aligning an optical element of an optical interferometer in which a beam of light interacts with the optical element and the optical element is tilted about first and second orthogonal axes to adjust the relative phase of components of the beam, wherein at least three parallel alignment beams of monochromatic light are directed through the interferometer towards respective detectors, the detectors being arranged in pairs such that tilting the optical element about the first axis does not affect the relative phase of components of each of the beams directed towards a first pair of detectors and tilting the optical element about the second axis does not affect the relative phase of components of each of the beams directed towards the second pair of detectors, a first estimate of an aligned optical element position is derived by determining from an output of at least one detector a first element position at which the amplitude of the beam incident on that detector is a maximum, second estimates of aligned element positions are derived by determining second element positions at which the phase differences between beams incident on each of the pairs of detectors are a minimum, and the element is aligned by moving it to a final position which is one of the second positions which is at or adjacent the first position.

The present invention also provides an apparatus for aligning an optical element of an optical interferometer in which a beam of light interacts with the optical element and the optical element is tilted about first and second orthogonal axes to adjust the relative phases of components of the beam, comprising means for directing at least three parallel alignment beams of monochromatic light through the interferometer towards respective detectors, the detectors being arranged in pairs such that tilting the optical element about the first axis does not affect the relative phase of components of each of the beams directed towards a first pair of detectors and tilting the optical element about the second axis does affect the relative phase of components

of each of the beams directed towards a second pair of detectors, means for deriving a first estimate of an aligned optical element position by determining from an output of at least one detector a first element position at which the amplitude of the beam incident on that detector is a maximum, means for deriving second estimates of aligned element positions by determining second element positions at which the phase differences between beams incident on each of the pairs of detectors are a minimum, and means for aligning the element by moving it to a final position which is one of the second positions which is at or adjacent the first position.

The first element position may be derived by calculating element position from the outputs of each of the detectors such that each calculated element position corresponds to a position at which the amplitude of the beam incident on the respective detector is a maximum, the first element position being determined by combining the calculated element positions. Each of the first and second pairs of detectors may include a common detector, three of the detectors being arranged in a triangular pattern. A fourth detector may also be provided to generate an additional amplitude signal.

A set of second element positions may be determined. The element may simply be aligned by moving it to the second position which is closest to the first element position. Alternatively or in addition the element may be moved to each of the set of second element positions in turn, the amplitude of outputs of at least one of the detectors may be monitored at each position, and the element may be moved to a final position corresponding to the second element position at which the monitored amplitude is a maximum.

An embodiment of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic representation of a Michelson interferometer;

Figure 2 illustrates the incorporation of additional optical sources and detectors which may be used in accordance with the present invention to initially align and maintain the alignment of mirror components;

Figure 3 shows one of the mirrors mounted on three actuators;

Figure 4 represents the disposition of four detectors relative to a plan view of one of the mirrors shown in Figures 1 and 2;

Figure 5 shows lines schematically representing tilt angles for which different pairs of detectors indicate detector signals are in phase;

Figure 6 represents attenuation gain with mirror tilt about one axis;

Figure 7 represents the amplitude of the output of the one of the detectors for different tilts in two orthogonal directions;

Figure 8 represents signals for all four detectors shown in Figure 4 assuming tilting about two orthogonal axes and the maintenance of one actuator in a fixed position;

Figure 9 represents the detector outputs shown in Figure 8 subject to an added displacement of all of the three actuators shown in Figure 3;

Figure 10 shows a typical detector output signal corresponding to tilting the mirror about one of the orthogonal axes whilst maintaining the mirror fixed relative to the other orthogonal axis;

Figure 11 represents the mirror positions at which the phase is constant as between the outputs of different pairs of detectors;

Figure 12 represents the variation of the magnitude of phase differences between tilts in the two orthogonal directions;

Figure 13 shows the position of points on the graph of Figure 12 at which the phase difference is a minimum; and

Figure 14 represents the amplitude of the output signals from the four detectors of Figure 4 for each of the nine labelled points of minimum phase difference shown in Figure 13.

Referring to Figure 1, the illustrated Michelson interferometer comprises a first mirror 1 which is fixed in position and a second mirror 2 which is displaceable in the direction of the arrow 3. The mirrors 1 and 2 are planar and are held at right angles to one another. A beam splitter 4 is inserted between the mirrors in the path of an incoming light beam 5. The optical components are arranged so that the beam splitter 4 reflects approximately 50% of the incident beam towards the mirror 1 but passes approximately 50% to the mirror 2. The reflected beams of light from the mirrors pass through the beam splitter or are reflected by the beam splitter and are recombined into a single beam 6 which is directed towards a NIR (near infra red) detector 7. The intensity sensed by the detector 7 depends upon the optical path

difference between the paths travelled by the two components beams. The optical path difference (retardation r) is varied by moving the mirror 2 relative to the beam splitter 4. This in turn varies the intensity of the light incident on the detector 7 in a way that makes it possible to derive the spectral structure of the incident light beam 5. This spectral structure can be used to determine characteristics of the light source and the material that the light has either passed through or been reflected from.

Figures 2, 3 and 4 illustrate an embodiment of the present invention which incorporates the essential components of a Michelson interferometer such as that shown in Figure 1 but in addition incorporates components which enable the initial alignment of the mirrors 1 and 2 and the maintenance of appropriate alignment during use of the instrument. The mirror 1 is supported on three actuators 8, 9 and 10, the mirror 1 facing a support 11 for the main detector 7 and four further detectors 12, 13, 14 and 15. The actuator 8 is aligned with the detector 12, the actuator 9 is aligned with the detector 13, and the actuator 10 is aligned with the detector 14. The detector 15 is located at the fourth corner of the square support 11.

Each of the detectors 12 to 15 is positioned so as to be arranged to detect a respective one of four parallel alignment control beams 16 two of which are shown in Figure 2. The alignment control beams 16 could be generated by separate monochromatic sources but generally will be generated by beams splitting a single beam delivered by a monochromatic source. Each of the beams 16 is directed through the instrument in exactly the same manner as the main beam 5 and therefore will be subject to beam splitting and recombination in exactly the same manner as the main beam 5. Thus displacement of the mirror 1 will affect all of the five beams passing through the instrument. When the mirrors 1 and 2 are perfectly aligned, the signals measured at the detectors 12, 13, 14 and 15 will be exactly in phase. If the actuators 8 and 10 are not moved but the actuator 9 is moved, the mirror 1 will tilt about a first axis extending parallel to the direction in which the actuators 8 and 10 are spaced apart. There will be no resultant change in the distance between the actuators 8 and 19 and the respective detectors 12 and 14. If in contrast the actuators 8 and 9 are not moved whereas the actuator 10 is moved, the mirror 1 will tilt about an axis parallel to the direction in which the actuators 8 and 9 are spaced apart and as a result the distance between the mirror supported by the actuator 10 and the aligned detector 14

will change whereas the distance between the portions of the mirror 1 adjacent the actuators 8 and 9 and the aligned detectors 12 and 13 will not change. Thus by appropriate control of the three actuators the mirror 1 can be tilted about two orthogonal axes so as to adjust the relative phase of components of the beams reaching each of the five detectors 7, 12, 13, 14 and 15. In embodiments of the invention there must always be the facility to tilt one of the components about two orthogonal axes and there must be at least three alignment beam and detectors arrangements to detect tilting about those axes. In the illustrated arrangement four alignment beam detector arrangements are provided but it will be appreciated that only three such arrangements are required.

It will be appreciated that the main beam 5 defines the optical axis of the instrument. The additional detectors and monochromatic alignment beams are disposed symmetrically around the main optical axis in alignment (after reflection in the beam splitter 4) with the corners of the mirror 1 and therefore also in alignment with the four detectors 12, 13, 14 and 15.

Although normally the symbols X, Y and Z are used to define a three-dimensional space with each of the symbols being applied to one of three mutually orthogonal axes, in this document those symbols will be used to represent extensions of the three actuators 8, 9 and 10. Thus extension of the actuator 8 results in a Y displacement, extension of the actuator 9 a Z displacement, and extension of the actuator 10 an X displacement. Such extensions result in tilting of the mirror 1. As described below, a ZY tilt will result if the Y actuator 8 is not moved whereas the Z actuator 9 is moved. Similarly, an XY tilt will result if the Y actuator is not moved whereas the X actuator 10 is moved. Tilting of the mirror 1 is described below in terms of XY and ZY tilt.

The detectors 12, 13, 14 and 15 are aligned respectively with the Y actuator 8, the Z actuator 9, the X actuator 10 and the corner of the mirror 1 diagonally opposite the Y actuator 8. These four detectors are therefore referred to below as the Y detector 12, the Z detector 13, the X detector 14, and the W detector 15, each of the detectors producing an output signal representative of displacement of the respective corner of the mirror 1.

Alignment is controlled in three distinct stages, that is a first stage which performs an approximate initial alignment based on monitoring the amplitude of the outputs of the detectors, a second stage which relies upon the relative phase of beams reaching the detectors to provide an estimate of improved accuracy, and a third stage which compares alternative estimates to ensure the accuracy of the second stage estimation.

In the first stage, the actuators are displaced in a predetermined pattern so as to obtain a two-dimensional image of diffraction patterns at each of the four detectors. The maximum amplitude points of each of the diffraction pattern images provides an estimate of a correct alignment position for the mirror for that detector. The four resultant estimates are then combined to produced an initial estimate of the correct alignment position. The objective is to align the centre of the diffraction pattern over the main detector 7 since this is the detector that is used to measure interferograms. The estimated alignment positions of the four detectors 12, 13, 14, 15 are used to produce a single estimate of the alignment position of the main detector 7. The relative position of each of the detectors (12, 13, 14, 15 in figure 4) with respect to the main detector 7 is known. Thus each of the estimates of the correct alignment position for the detectors 12, 13, 14, 15 can by simple geometry be used to obtain an estimate of the correct alignment position for the main detector 7. These four resulting estimates of the correct alignment position for the main detector are combined (by averaging for example) to obtain a single estimate of the alignment position for the main detector.

The estimates produced by each of the four detectors will be somewhat unreliable due to estimation errors resulting from the noisy nature of the detector signals. The second stage therefore uses phase information from the two-dimensional images rather than the amplitude information as used in the first stage. This second stage relies upon the fact that the maximum amplitude in the detector signals should occur at a point when all four detector signals are in phase. Thus the two dimensional images are used to make a further plot of the lines at which the signals from the XY pair of detectors 12 and 14 and a ZY pair of detectors 12 and 13 are in phase.

Given that the XY detectors 12 and 14 are spaced apart in a direction perpendicular to the direction of separation of the YZ detectors 12 and 13, any ZY tilt will not alter the relative phases of the X and Y detectors 12 and 14. Therefore, there will be a number of XY tilt positions at which the outputs of the XY detectors 12 and 14 will be in phase regardless of the output of the Z detector 13 and equally there will be a number of values for ZY tilt at which the outputs of the Y and Z detectors 12 and 13 will be in phase regardless of the output of the X detector 14. Referring to Figure 5, this schematically represents XY and ZY tilt of the mirror 1. The cross 16 represents tilt values corresponding to the initial alignment estimate produced by the first stage of the alignment process. The line 17 represents an XY tilt value for which the outputs of the Y and Z detectors 12 and 13 are in phase regardless of XY tilt and the line 18 represents a ZY tilt value for which the outputs of the X and Y detectors 12 and 14 are in phase regardless of XY tilt. The point of intersection 19 of lines 17 and 18 represents a second estimate of the true tilt position corresponding to alignment.

In practice, there will be a number of lines parallel to the line 17 each of which represents a possible aligned position and a number of lines parallel to the line 18 each of which corresponds to a possible aligned position. The point of intersection selected is that which is closest to the initial estimated alignment position represented by cross 16. Given that the sets of lines parallel to lines 17 and 18 are spaced at 2π intervals in the ZY and XY tilt directions it may be that the "correct" point of intersection is not that which is closest to the initial estimate 16 but rather is a point of intersection slightly further away from the initial estimate position represented by cross 16. The third stage of the alignment process ensures that the "correct" point of intersection is selected.

In the third stage, alternative alignment positions are investigated and further corrections made if necessary on the basis of that investigation. Having initially selected the point of intersection 19 closest to the initial point 16, the points of intersection for the two closest adjacent in-phase positions in both the XY and ZY tilt directions are identified. In Figure 5, these positions are represented by the additional lines 20 parallel to line 17 and the additional lines 21 parallel to line 18. The lines 17, 18, 20 and 21 intersect at nine points, that is the intersection point 19 and the eight

intersection points spaced around point 19. The mirror 1 is scanned backward and forward in the same procedure as is used when collecting data for the two-dimensional images relied upon in the first stage. The detector signals which result will be a set of sinusoidal signals which are maintained in phase during the scan to maintain the initial alignment of the mirrors. This process of dynamic control is known and has been discussed in for example US Patent No. 4,413,908. In addition to this known dynamic control however in the third stage of the alignment process the eight points around the intersection point 19 are systematically probed. Thus during a single scan, the dynamic control system moves the mirror in turn to each of the eight positions represented by the intersection point surrounding point 19. The amplitudes delivered by the four detector signals are measured at each of these eight points and compared with the amplitude at the mirror position corresponding to the intersection point 19. These monitored amplitudes are equivalent to measurements of the amplitude signals during the first stage of the process. By comparing the measured amplitudes, a further estimate of the accuracy of mirror alignment is derived. For example, if this investigation indicated that the amplitude at the point corresponding to intersection point 22 in Figure 15 was greater than at intersection point 19, the system would automatically move the mirror on the basis that the "correct" aligned position is the XY and ZY tilt corresponding to the intersection point 22.

The alignment process described in general terms above will now be described in greater detail with reference to Figures 6 to 14.

When the mirrors in a Michelson interferometer are tilted and the light source is a monochromatic source (usually a laser) interference patterns are generated which are scanned across the detector. The signals measured at the detector depend on the optical path difference for the light from the two mirrors (mirrors 1 and 2 in Figure 1) and also on any misalignment between the mirrors. The interference pattern at each of the four detectors 12 to 15 represented in Figure 4 is determined by the optical path difference, and the signal at each end of the detectors is attenuated depending on the amount of the misalignment. (The attenuation also depends on the diameter of the detectors, with larger detectors being more sensitive to misalignments). The attenuation gain A at a detector can be approximated by:

$$A = \frac{2J_1(4\pi\sigma r\alpha)}{4\pi\sigma r\alpha}$$

Where σ is 1/(source wavelength), r is the detector radius, J_1 is the Bessel function of the first kind, and α is the misalignment angle. Figure 6 shows the theoretical attenuation for a laser source of wavelength of 670nm, a detector of radius of 2mm and the mirror tilt varying from -0.0005 radians to 0.0005 radians. This tilt is obtained with actuators 2cm apart and moving 20 microns.

When the actuators are used to tilt the mirror 1 about axes ZY and YX the detector signal at say W detector 15, (D_w), is given by the expression:

$$D_w = Mean + A\,k\,Cos\left(\frac{Optical\ Path\ Difference}{Wavelength} * 2 * \pi\right)$$

where *Mean* is the mean detector signal, k is the peak modulation by the interferometer, and the *Optical Path Difference* is for the particular detector.

Thus, if the Y piezoelectric actuator 12 is maintained stationary, Figure 7 shows the expected amplitude variations in the detected W signal, where the optical path difference is the sum of the two movements of the X and Z actuators 13 and 15 relative to the Y actuator 12. The ZY tilt changes the difference between the optical path difference at the Z detector and that at the Y detector 12.

The two-dimensional plot of Figure 7 shows the contours of detector signal magnitude for the various tilts. The maximum detector signal is at the centre (corresponding to zero tilt in this idealised diagram). Given the two-dimensional plot of Figure 7, it is possible to identify the correct alignment position by finding the point at which the detector signal is a maximum.

Greater accuracy can be achieved by monitoring the amplitude at all four detectors. Figure 8 shows plots for all four detectors, assuming no movement of Y actuator 12.

The signals for detectors X, W and Z shown in Figure 8 can be used to determine the mirror tilt position giving a maximum amplitude signal, but the signal for Y is not useful because the Y actuator 12 is not moving. To get a useful signal

from all four detectors, a ramp change is added to the all the actuators at the same time as changing the XY and ZY tilts. Figure 9 show the result with an extra 20 micron movement in the optical path difference obtained by adding such a ramp. The orientation of the contours can be changed if desired by adding the ramp in different ways.

The two-dimensional plots shown in Figure 9 can be used to obtain an estimate of the correct alignment point for each detector using a method that finds the maximum point in the envelope of the two-dimensional surfaces. These estimates, together with the geometry of the detectors and the main NIR detector 7, can be used to obtain four estimates of the correct alignment point for the main NIR detector.

A number of methods can be used to find the maximum points from the four detector signals. In one method, the tilts for minimum attenuation can be found by fitting a quadratic surface to the peaks of the detector signals, in the individual scans. Figure 10 shows a typical expected detector signal for a scan in the XY tilt direction keeping the ZY tilt constant. At the peaks on this curve the cosine term in the detector output will be unity. Therefore a surface fitted to the peaks will approximate $kA(\theta)$, where k is a constant depending on the detector gain and $A(\theta)$ is the attenuation due to tilt angle θ. So the peaks give points on the attenuation surface which is approximately a two dimensional quadratic. Least squares fitting can be used to fit a quadratic to all the peaks, which are sufficiently large. For example, all the peaks where the gain A is at least 0.7 may be used. This then give the points of minimum attenuation for each detector which indicate the tilts required to align the mirrors at the detectors. Any individual detector could be used, but a better estimate is obtained by using all four detectors.

It is possible to find the overall optimum by successive searches along orthogonal directions. For example first scan through a set of XY tilts while keeping the ZY tilt constant at ZY_0. This gives a "cut" through the surface as in Figure 10. One-dimensional quadratics can be fitted to the larger peaks in order to find the peak of the envelope containing the signal. This gives a best XY tilt XY_1 for the ZY tilt ZY_0. Next scan through a set of ZY tilts while keeping the XY tilt constant at XY_1. This gives another "cut" through the surface as in Figure 10. One-dimensional

quadratics can be fitted to the larger peaks in order to find the peak of the envelope containing the signal. This gives a best ZY tilt ZY_1 for the original XY tilt XY_1. The process is then repeated with the ZY tilt ZY_1. This iteration converges fairly rapidly due to the overall surfaces in Figure 9 having circular symmetry. A separate search has to be made for each detector.

The above procedure is used to obtain the estimates of the correct alignment angle for each detector – and these in turn give four estimates of the correct alignment position for the main detector 7 (Figure 4). These four estimates may be combined to produce an initial estimate of the "correct" alignment position.

In the second stage of the process, the relative phases of the detector signals are used to improve the estimate of the true detector amplitude maximum. When the mirrors are exactly aligned, the optical path differences for the four detectors will be equal, and the detector signals will be in phase. Therefore the correct alignment point of the mirrors occurs at a pair of XY and ZY tilts which give the same phases for each of the detectors 12 to 15. Figure 5 shows lines for which the X and Y detectors are in phase and the Z and Y detectors are in phase for the maximum detector amplitude. However the phase is periodic and so these lines repeat at tilt intervals of a wavelength, so that the true maximum in the detector amplitude maybe at any of the intersections of the zero relative phase lines. The tilt angles corresponding to these lines of zero relative phase are calculated and then used to improve the estimates of the detector alignment points obtained from the first stage.

At each of the peaks of the detector signals found in the first stage, the phase difference will be zero or $2\pi n$, where n is an integer. Hence by linear interpolation between the peaks we can find the phase of the signal at the particular detector. This can be done for each point on the XY, ZY tilt planes shown in Figure 9. The X and Y detectors will have equal phase along a set of zero relative phase lines one wavelength apart in tilt actuator positions, with constant XY tilt. The Z and Y detectors will have equal phase along lines with constant ZY tilt. There should be a grid of points where these lines intersect, which are a wavelength apart in tilt angle in each direction, and where the phases of all four detector signals are equal. The lines of equal phase can be calculated from the amplitude plots (Figure 9) using linear interpolation. Figure 11

shows the results of calculating the lines of equal phase from the plots shown in Figure 9.

The intersection points of the lines in Figure 11 correspond to points at which all detectors have the same phase. One of these intersection points should correspond to the zero phase point at which the amplitude is a maximum. In practice however this will not generally be the case due to inaccuracy in the estimation of the position of maximum amplitude. In addition, the lines in Figure 11 should be straight, but the calculation method used is necessarily approximate. Therefore the accuracy of the second stage process is increased by finding the grid of points where the estimated phases of the detectors are closest. One of the ways of finding these points of 'closest phase' is to find the sum of the magnitudes of the phase differences between the detectors. Figure 12 shows the contours of the surface representing the sum of the magnitudes (again this picture is approximate due to the calculation method). The local minima are shown by crosses. These crosses correspond to estimates of the tilt positions at which the lines of equal detector phases cross, and all the detector phases are equal. The area is then divided into squares, and the point of 'closest phase' in each square is plotted to form the grid pattern of Figure 13.

One of these grid points in Figure 13 corresponds to the mirrors being aligned with all four optical path differences being equal. The grid point nearest to the estimate obtained in the first stage is then selected as the best estimate of the true alignment point. Note however that this point (labelled 1 in Figure 13) is an estimate, and the points around it (labelled 2 to 9 in Figure 13) could also be accepted as reasonable estimates of the true alignment position. These points are tested in the third stage of the alignment algorithm to check the accuracy of the alignment and test for a better alignment point during the operation of the interferometer.

During normal operation, the mirrors 1, 2 are moved with respect to each other by either applying the same displacement to all piezo-actuators attached to mirror 1 or by having a separate device to move the other mirror 2. The normal sequence of operation will be that the mirrors will be initially aligned using the methods described in the first and second stages. This gives the set of tilts that are required to place the interferometer mirrors in alignment. A separate dynamic control scheme is then used

during the collection of interferograms. The function of the dynamic control system it to keep the mirrors in alignment during the displacement of the moving mirror. This is done by measuring the laser detector signals X, Y, Z, during the moving mirror scan.

The laser source is monochromatic, and therefore the detector signals during the scan are a set of sine waves. The dynamic control scheme measures the relative phases of the detector signal sine waves and adjusts the actuator tilts to maintain the relative phases at zero. If the initial alignment algorithm worked correctly, then the zero phase point corresponds to the zero relative phase point marked as 1 in Figure 13, and hence the zero phase point which gives the maximum amplitude signal at the detector 7. However, the point 1 in Figure 13 is in fact an estimate of the correct alignment position, and the surrounding points (labelled 2 to 9) are also possible points for the correct alignment position. If stage the first and second stages of the initial alignment were grossly in error then the correct alignment point might be at some other zero phase point in the grid on Figure 13.

The third stage of the alignment process is performed during scanning of the mirror. The validity of the selected grid point (point 1) is checked within the dynamic control process by performing a test scan during which the tilts are periodically changed to align the mirrors at grid points 2 to 9 (in Figure 13) in turn. The detector signal amplitudes at each of the grid points are then measured. The amplitudes measured at these grid points are in fact points on the two-dimensional amplitude plots for each of the detectors. Thus a further curve fitting can be used to determine an estimate of the position of maximum detector signal for each detector. This can be done while scanning the optical path difference through thirty wavelengths and so can be done in a single scan of the instrument.

Figure 14 shows the detector signal for a pattern of tilts going round the points number 1 to 9 on Figure 13. Between the lines 23 and 24 the tilt positions are changing. The tilt positions for the control process are then kept constant until the next line 23. The peaks of the quadratic fits to this data are used to either confirm that the current grid point 1 is the correct alignment point, or to pick another grid point as a better estimate of the correct alignment point, or to initiate a re-alignment from

stage 1. In the case illustrated in Figure 14, grid point 6 would be selected as the point providing the greatest amplitudes.

Thus, the invention provides a method of initially aligning the mirrors in a two-beam interferometer and subsequently refining and checking the alignment during normal operation of the interferometer. In summary, the process relies upon three stages. In the first stage, a set of three piezo actuators is scanned through a pattern which produces two-dimensional images of detector signal amplitude for each of four detectors. The point at which the envelope of these two-dimensional plots reaches a maximum gives an estimate of the correct alignment position for each detector. Using the known geometry of the instrument these each form a separate estimate of the location of the correct alignment position (as defined by a set of tilts of one of the mirrors) for the main detector.

The second stage uses the fact that when the mirrors are aligned the relative phases of the detectors are zero, and that when the mirror is tilted in one axis the relative phases in the other axis are not altered. This is used to form a grid of zero relative phase points – one of which must be the point at which the mirrors are aligned. The best of these candidate alignment points is selected as the one nearest to the correct alignment estimated in the first stage.

The third stage of the alignment algorithm takes place during the scanning of the mirror under dynamic control. A set of alternative zero relative phase points that are around the selected point are visited and the amplitudes of the detector signals at these points is used to provide a further estimate of the correct alignment point. If this is the same as the current alignment point then no action is taken, if it is different then the instrument either moves to that point or initiates a full re-initialisation of the interferometer.

The invention provides several benefits. Firstly, initial alignment may be automatically implemented, thereby removing the necessity for this task to be carried out by a skilled operator. Secondly, alignment may be continuously or frequently checked and maintained. This increases confidence in the integrity of the measurement and offers the possibility of an automatic warning if for any reason the alignment fails and cannot be automatically restored. This has obvious benefits in any

situation where the instrument is used in an application where there are regulatory, safety or other implications in the event of a loss of measurement accuracy. Thirdly, it prevents a progressive deterioration in performance after initial alignment, and so has implications for reducing the amount of routine service that may be required. Related to this is the possibility that the instrument can be designed and engineered to lower tolerances, especially with regard to mechanical stability, thereby reducing costs. The ability of the instrument to maintain alignment during operation offers the potential for using the instrument in adverse conditions in which prior art instruments would not be capable of reliable operation for extended periods of time. This is especially important when it is desired to extend the use of a measurement currently effected as a laboratory check onto a production line for example. The economic benefits of making a measurement continuously on a production line are frequently much greater than making the same measurement intermittently on samples taken from that line. Benefits typically include the saving of energy, the maintenance of high product quality and the reduction of the quantity of waste or defective product.

CLAIMS

1. A method for aligning an optical element of an optical interferometer in which a beam of light interacts with the optical element and the optical element is tilted about first and second orthogonal axes to adjust the relative phase of components of the beam, wherein at least three parallel alignment beams of monochromatic light are directed through the interferometer towards respective detectors, the detectors being arranged in pairs such that tilting the optical element about the first axis does not affect the relative phase of components of each of the beams directed towards a first pair of detectors and tilting the optical element about the second axis does not affect the relative phase of components of each of the beams directed towards the second pair of detectors, a first estimate of an aligned optical element position is derived by determining from an output of at least one detector a first element position at which the amplitude of the beam incident on that detector is a maximum, second estimates of aligned element positions are derived by determining second element positions at which the phase differences between beams incident on each of the pairs of detectors are a minimum, and the element is aligned by moving it to a final position which is one of the second positions which is at or adjacent the first position.

2. A method according to claim 1, wherein the said first element position is derived by calculating element positions from the outputs of each of the detectors such that each calculated element position corresponds to the position at which the amplitude of the beam incident on the respective detector is a maximum, and determining the first element position by combining the calculated element positions.

3. A method according to claim 1 or 2, wherein three detectors are provided, one detector being included in each of the first and second pairs of detectors.

4. A method according to any preceding claims, wherein four detectors are provided.

5. A method according to any preceding claim, wherein a set of second element positions is determined, and the element is aligned by moving it to the second position which is closest to the first element position.

6. A method according to any one of claims 1 to 4, wherein a set of second element positions is determined, and the element is moved to each of the set of second element positions in turn, the amplitude of an output of at least one of the detectors is monitored at each position, and the element is moved to the second element position at which the monitored amplitude is a maximum.

7. An apparatus for aligning an optical element of an optical interferometer in which a beam of light interacts with the optical element and the optical element is tilted about first and second orthogonal axes to adjust the relative phases of components of the beam, comprising means for directing at least three parallel alignment beams of monochromatic light through the interferometer towards respective detectors, the detectors being arranged in pairs such that tilting the optical element about the first axis does not affect the relative phase of components of each of the beams directed towards a first pair of detectors and tilting the optical element about the second axis does affect the relative phase of components of each of the beams directed towards a second pair of detectors, means for deriving a first estimate of an aligned optical element position by determining from an output of at least one detector first element position at which the amplitude of the beam incident on that detector is a maximum, means for deriving second estimates of aligned element positions by determining second element positions at which the phase differences between beams incident on each of the pairs of detectors are a minimum, and means for aligning the element by moving it to a final position which is one of the second positions which is at or adjacent the first position.

8. A method for aligning an optical element of an optical interferometer substantially as hereinbefore described with reference to the accompanying drawings.

9. An apparatus for aligning an optical element of an optical interferometer substantially as hereinbefore described with reference to the accompanying drawings.

ABSTRACT

A method for aligning an optical element of an optical interferometer in which a beam of light interacts with the optical element and the optical element is tilted about first and second orthogonal axes to adjust the relative phase of components of the beam. At least three parallel alignment beams of monochromatic light are directed through the interferometer towards respective detectors. The detectors are arranged in pairs such that tilting the optical element about the first axis does not affect the relative phase of components of each of the beams directed towards a first pair of detectors and tilting the optical element about the second axis does not affect the relative phase of components of each of the beams directed towards the second pair of detectors. One detector may form part of each of the first and second pairs of detectors. A first estimate of an aligned optical element position is derived by determining from an output of at least one detector a first element position at which the amplitude of the beam incident on that detector is a maximum. Second estimates of aligned element positions are also derived by determining second element positions at which the phase differences between beams incident on each of the pairs of detectors are a minimum. The element is aligned by moving it to a final position which is one of the second positions which is at or adjacent the first position. A set of second element positions may be determined, the element being moved to each of the set of second element positions in turn. The amplitude of outputs of at least one of the detectors may then be monitored at each of the second element positions to which the element is moved, and the element may be moved to the final position which corresponds to the position at which the monitored amplitude is a maximum.

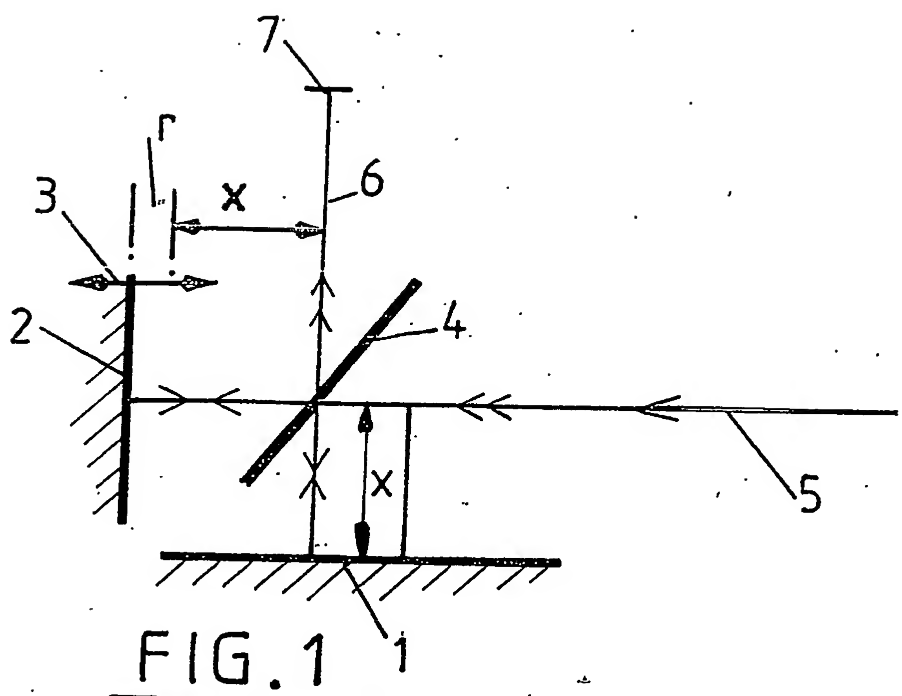


FIG.1

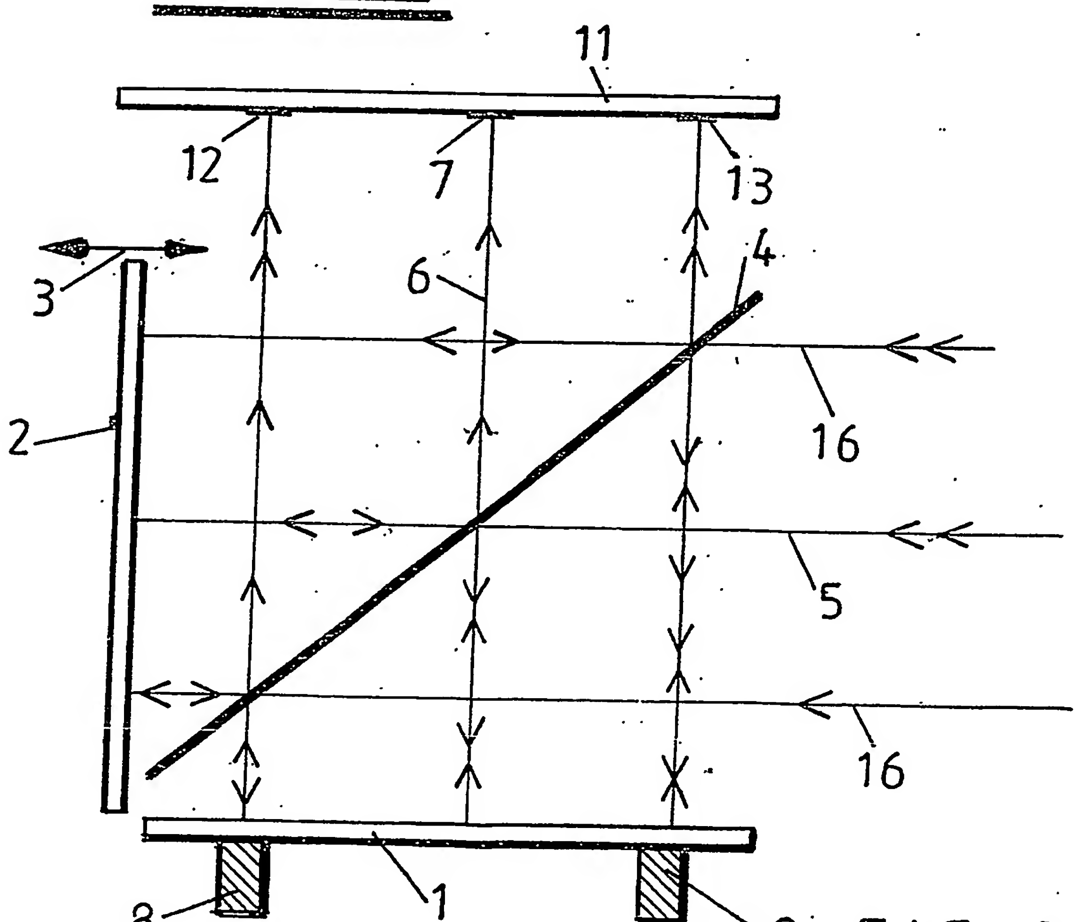


FIG.2

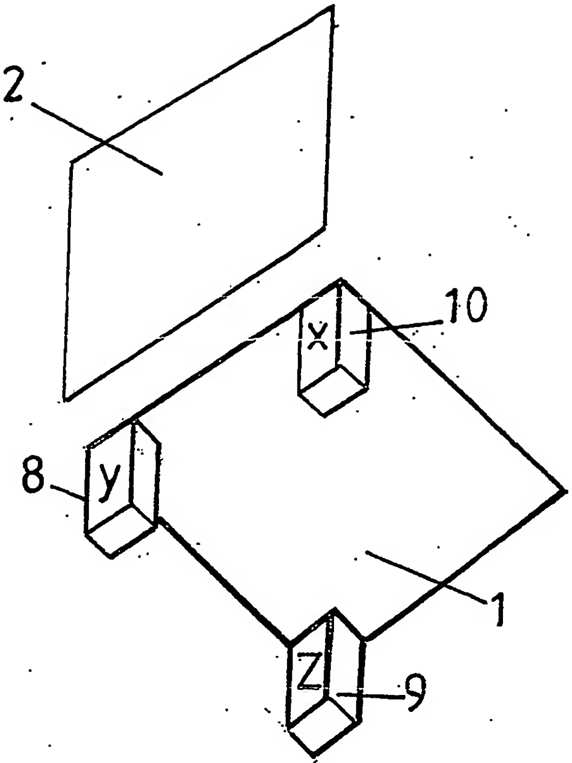


FIG.3

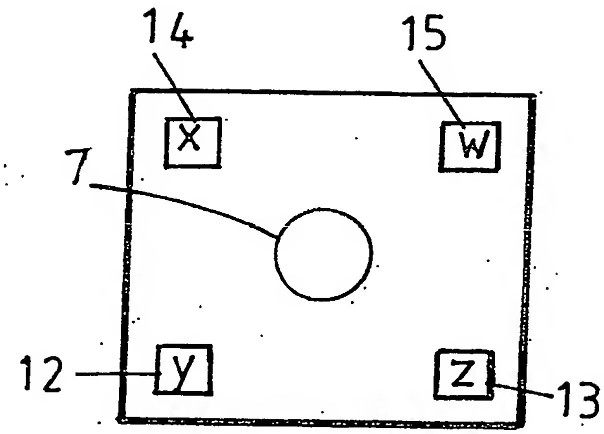


FIG.4

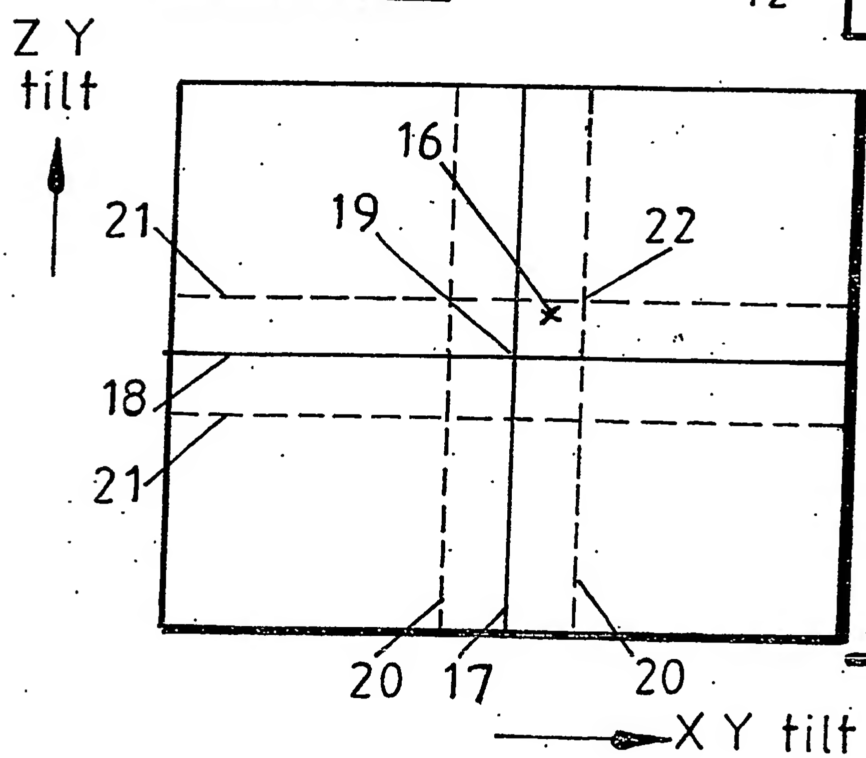


FIG.5

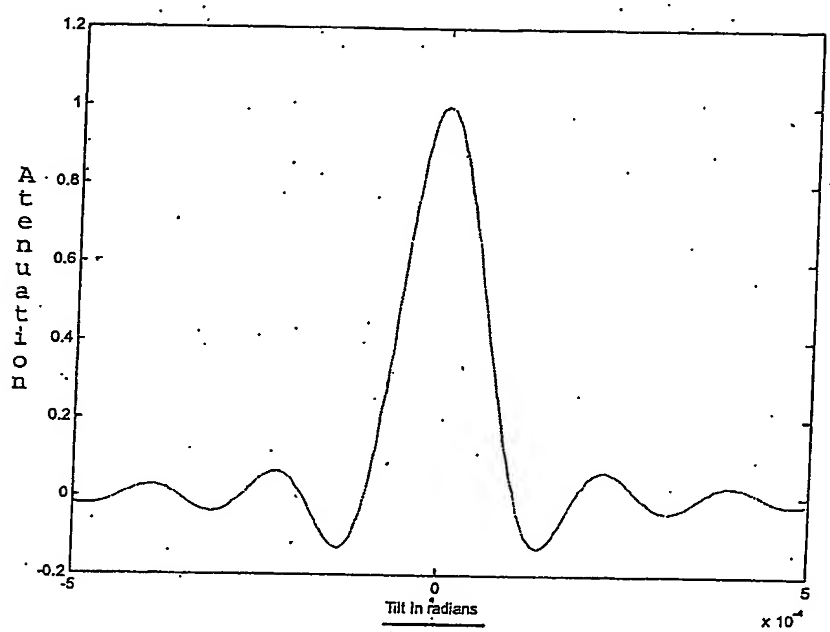


FIG.6

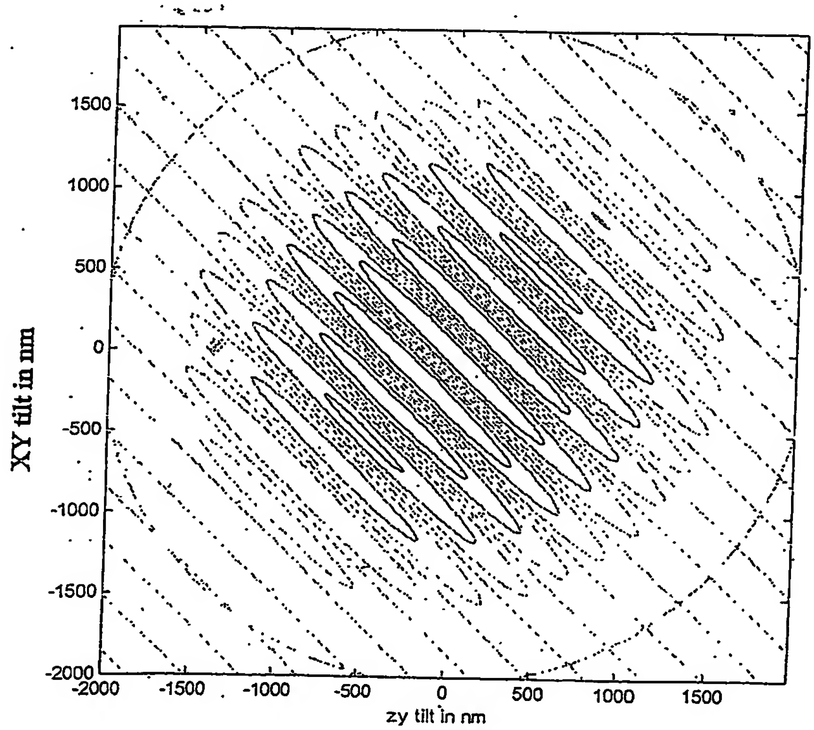


FIG.7

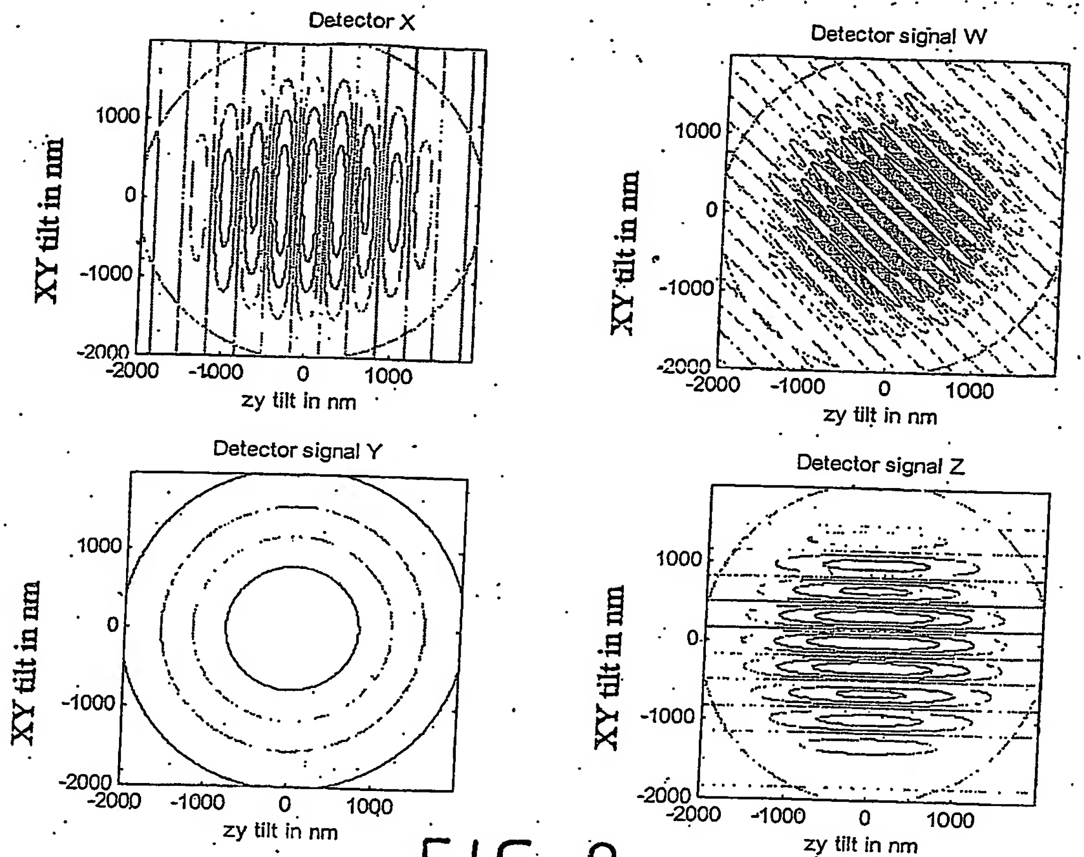

Detector X
Detector signal W
Detector signal Y
Detector signal Z
XY tilt in nm
zy tilt in nm
1000
0
-1000
-2000
-2000
-1000
0
1000

FIG. 8

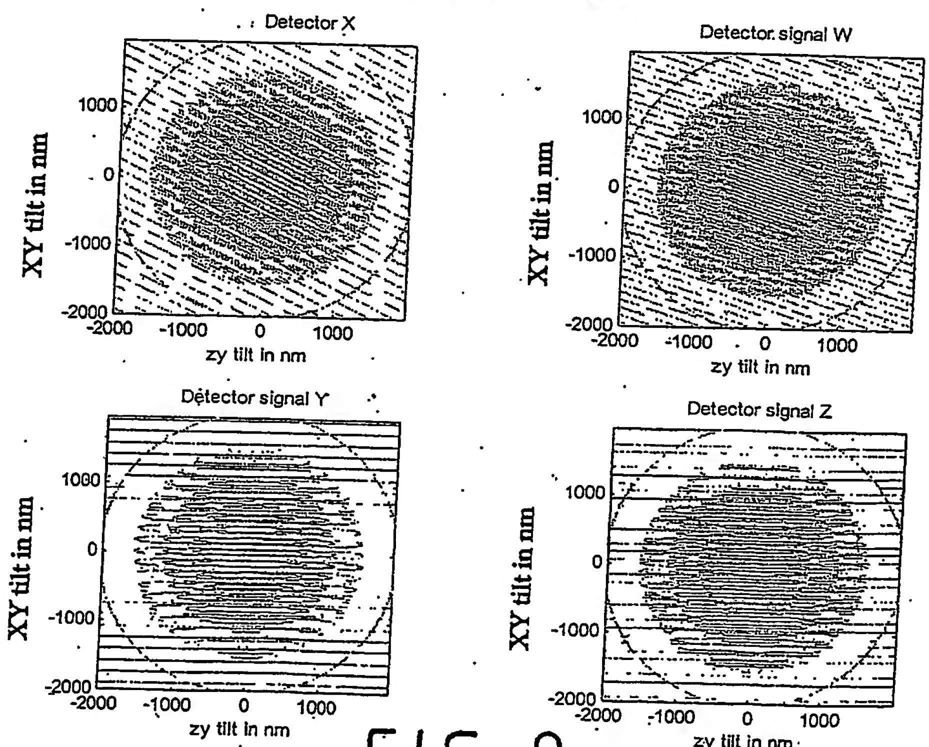
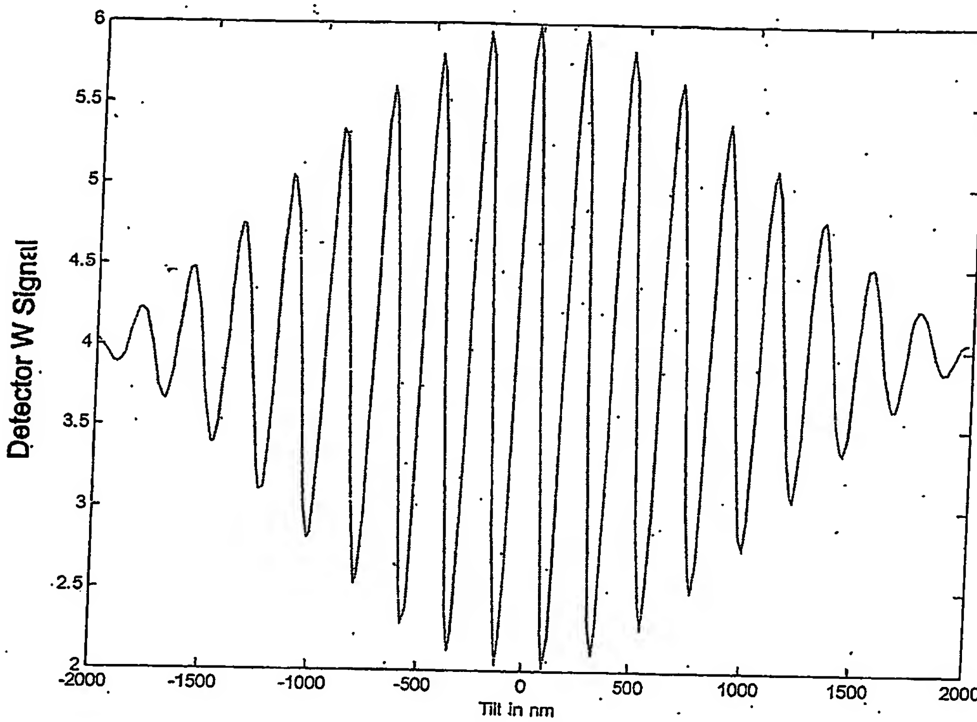

Detector X
Detector signal W
Detector signal Y
Detector signal Z
XY tilt in nm
zy tilt in nm
1000
0
-1000
-2000
-2000
-1000
0
1000

FIG. 9



Detector W Signal
Tilt in nm
6
5.5
5
4.5
4
3.5
3
2.5
2
-2000
-1500
-1000
-500
0
500
1000
1500
2000

FIG. 10

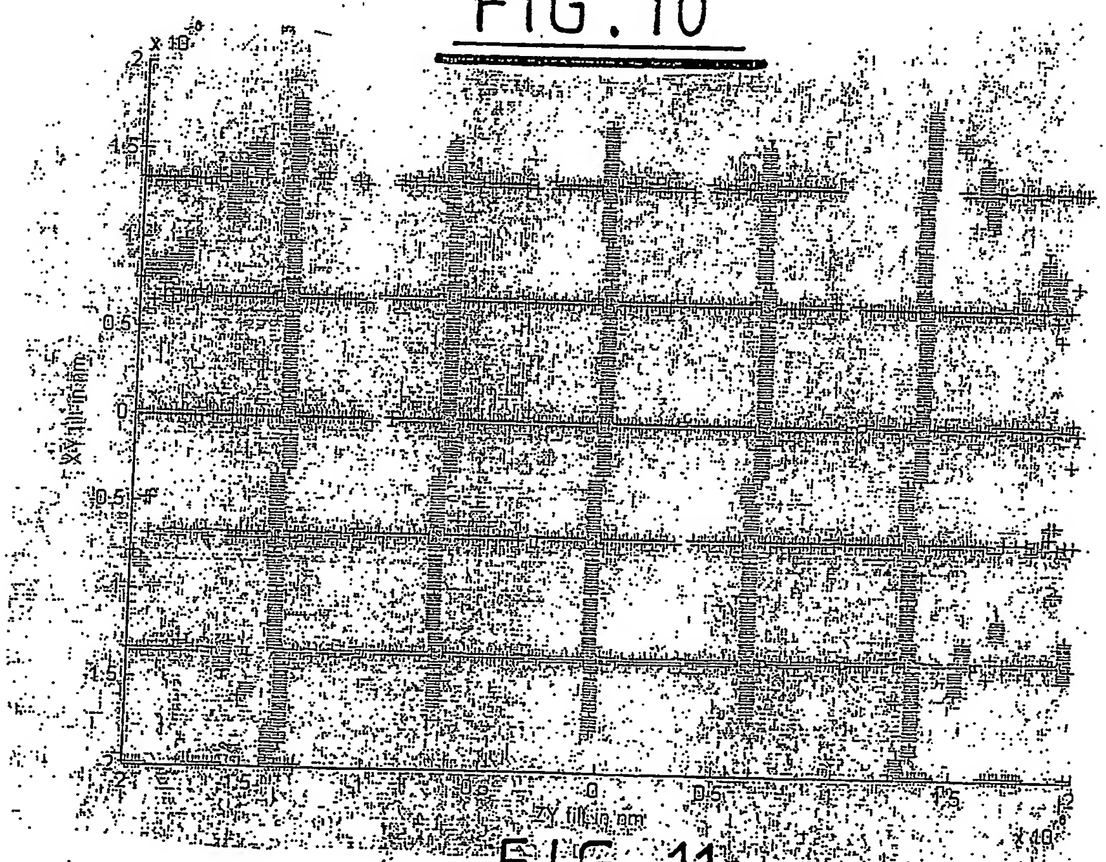


FIG. 11

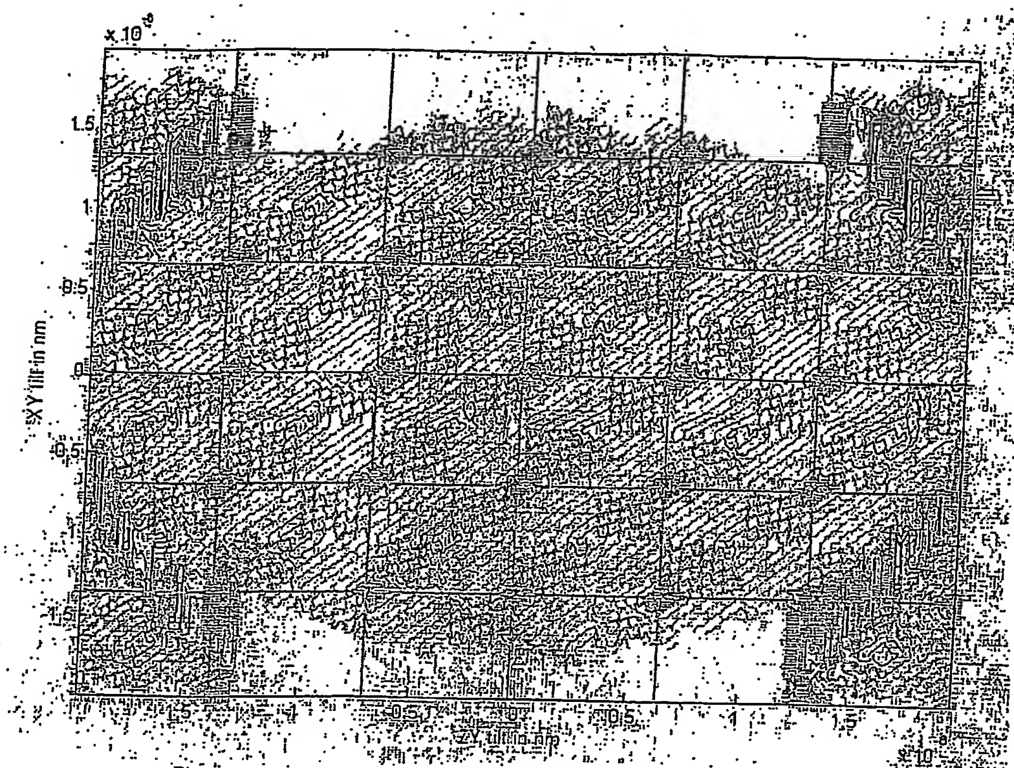

x 10^-6
1.5
1
0.5
0
-0.5
-1
-1.5
XY tilt in nm
-1.5
-1
-0.5
0
0.5
1
1.5
ZY tilt in nm
x 10^-6

FIG. 12

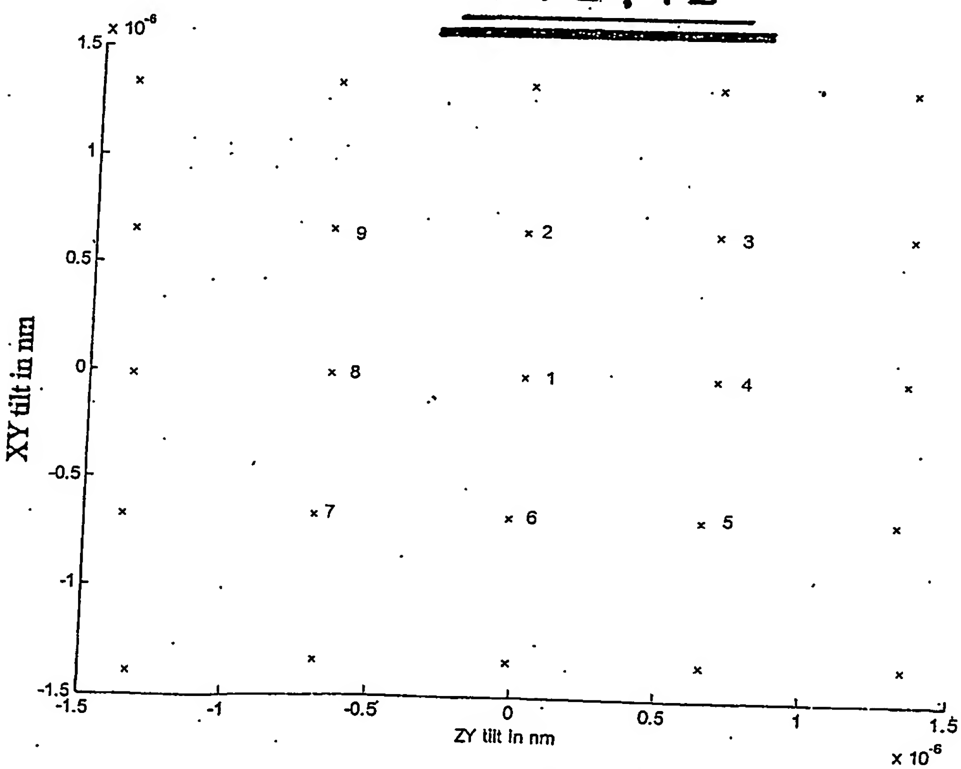
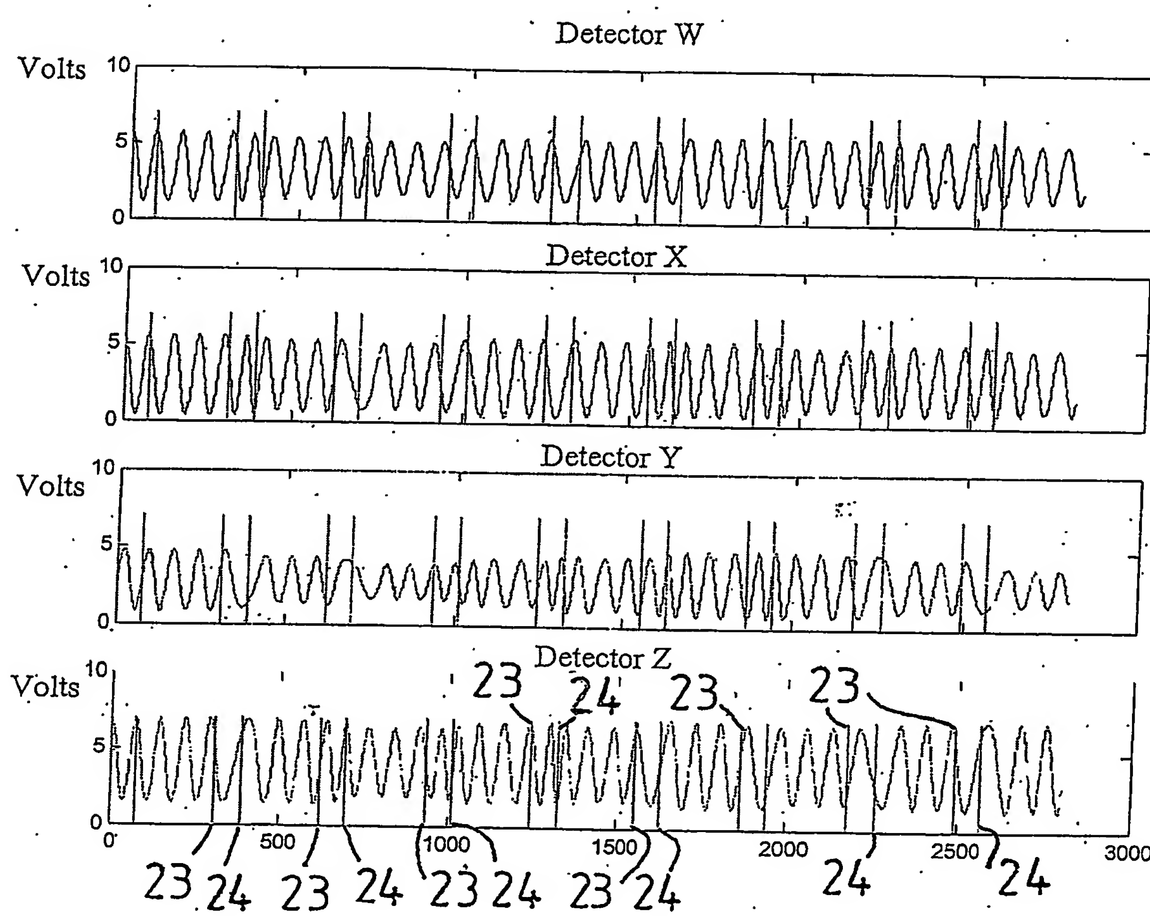

x 10^-6
1.5
1
0.5
0
-0.5
-1
-1.5
XY tilt in nm
9
2
3
8
1
4
7
6
5
-1.5
-1
-0.5
0
0.5
1
1.5
ZY tilt in nm
x 10^-6

FIG. 13


Detector W
Volts
10
5
0
Detector X
Volts
10
5
0
Detector Y
Volts
10
5
0
Detector Z
Volts
10
5
0
0
500
1000
1500
2000
2500
3000
23
24
23
23
23
24
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23
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24
24

FIG. 14

PCT Application
GB0303664